EFFECT OF PHASE DELAY ON LOW FREQUENCY OPERATION OF FLUX FOCUSING EDDY CURRENT PROBE

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INTRODUCTION

The operation of the Flux Focusing Eddy Current Probe has been found to yield critical information on the thickness of the material being inspected [1-2]. The design of the probe forces the low frequency magnetic fields to diffuse through the sample in order to link with the pickup coil. An attenuation of the magnetic field results such that the pickup coil output is inversely related to the material thickness [2]. In extending the technique to thicker and/or layered materials, however, an apparently anomalous behavior is sometimes seen in which a small increase in the probe output occurs with increasing material thickness. This paper will clarify the underlying principles involved with the probe during low frequency operation and explain the apparent anomaly in terms of the phase shifting of the magnetic field with diffusion depth. A phasor addition model will be presented which accounts for the observed experimental results, and implications of the phenomena on material testing will be discussed.

THICKNESS GAUGING WITH FLUX FOCUSING EDDY CURRENT PROBE

The Flux Focusing, or Isolated Field, Eddy Current Probe is the extension of the Self Nulling Eddy Current Probe into the low frequency regime. Whereas the Self Nulling Probe (optimized for surface flaw detection) is typically operated at or above 70 kHz, it is the behavior of this same probe between 1 and 50 kHz which provides for an accurate measure of material thickness and therefore for the detection of corrosion damage. Fig. 1 displays a schematic diagram of the probe along with typical oscilloscope traces of the output voltage of the probe when placed on different thickness aluminum sheets. The data for this figure was acquired at an operating frequency of 7 kHz. The attenuation of the output signal with increasing material thickness is quite apparent. This trend is further exemplified in fig. 2 which shows the probe output as a function of frequency for various thickness aluminum plates [3]. Based on the data shown in figs 1 and 2 both a single layer and a multi-layer corrosion detection/thickness gauge have been designed, built and tested [3-5]. Both systems are based upon measuring only the amplitude of the pickup coil output and, overall, both systems work well up to a total material thickness of approximately 0.1" in aluminum alloys. Further information on the two prototypes is available in the cited references.

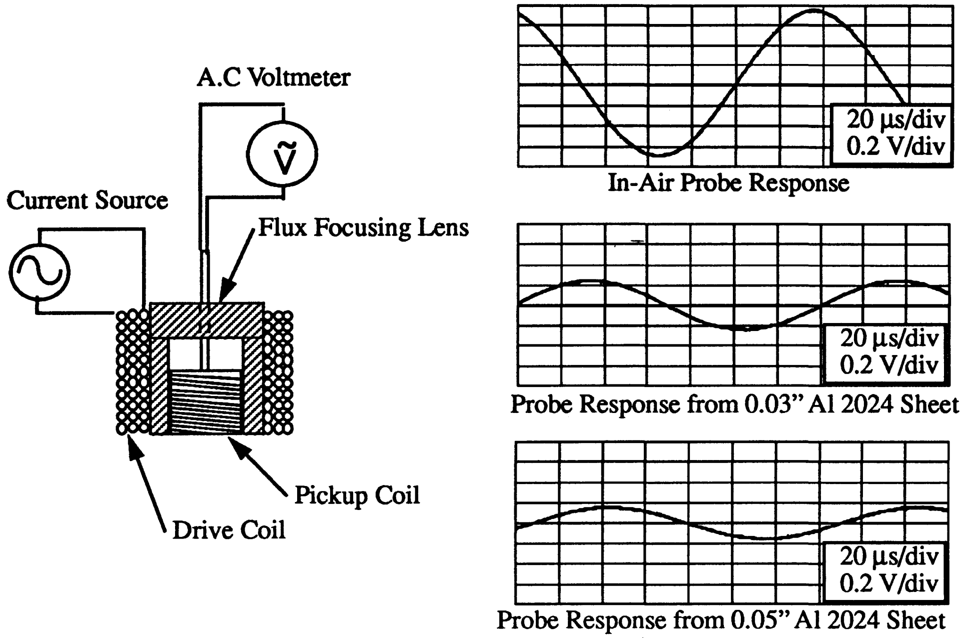


Fig. 1 Schematic probe diagram and typical signals from various thickness aluminum sheets.

An important application area of the multi-layer inspection system is detecting corrosion in the airframe lap-splice joint. In this joint two thin aluminum alloy plates overlap and are riveted together. The overlapping area is approximately 4" wide, and is held together with three rows of rivets, the center row of which attaches the skin panels to the airframe stringer. This area is susceptible to corrosion damage originating at the surface between the two panels. The multi-layer corrosion detection instrument was designed to measure the thickness of the top and bottom surfaces as well as the air-gap between the two sheets from a single sided inspection. In testing a Boeing 737 type joint the presence of the stringer causes the total thickness to exceed the 0.1" limit mentioned earlier. It was expected that measurements taken over the stringer would cause inaccuracies in the measurement of the bottom panel but would have little effect on the measurement of the thickness of the top

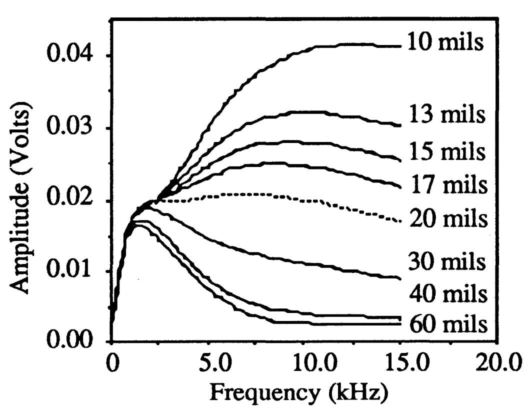


Fig. 2. Probe response as a function of drive frequency and material thickness [3].

panel and the air gap. It was therefore disturbing when the presence of the stringer caused significant errors in these measurements. In tracing the cause of the errors it was found that the additional increase in total material thickness caused an increase in the output voltages at the higher frequencies. This is in opposition to the data shown in figs 1 and 2 and to the model from which the thickness values were being extracted. A detailed investigation into the cause of the amplitude reversal was therefore initiated in order to clarify the operational characteristics of the probe and improve the accuracy of measurements taken on thicker samples.

LOW FREQUENCY OPERATION OF FLUX FOCUSING EDDY CURRENT PROBE

The finite element method can be used to investigate the energy interaction of the Flux Focusing Eddy Current Probe with a metallic sample. Fig. 3 displays the results of an axi-symmetric finite element model for the probe operating at 10 kHz above 1.0 and 2.0 mm aluminum plate samples. In fig. 3a. the magnetic flux, flowing along equipotential lines, is seen to penetrate through the sample. In contrast, the flux lines are completely contained in the 2.0 mm sample of fig. 3b.

The magnetic flux lines which link with the pickup coil will induce a voltage across the pickup coil leads according to Faraday's law of electromagnetic induction [6]. The induced probe output voltage is given by,

$$V = -NA\frac{dB_Z}{dt},$$

$$V = -i\omega NAB_{Z0},$$

where V is the induced probe output voltage, N is the number of turns on the pickup coil, A

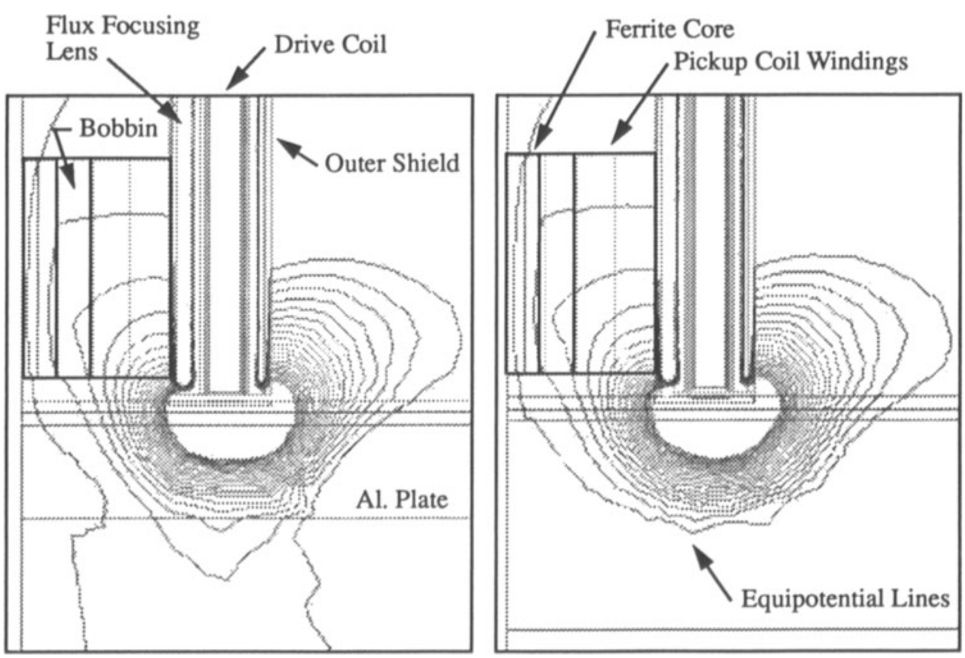


Fig. 3a. Axisymmetric FEM results for probe placed above 1.0 mm Al. plate.

Fig. 3b. Axisymmetric FEM results for probe placed above 2.0 mm Al. plate.

is the cross sectional area of the pickup coil, and $B_Z = B_{Z0}Exp[i(\omega t + \phi)]$ is the z component of the magnetic flux density with frequency ω and phase ϕ. Fig 4 displays the amplitude and phase of the voltage calculated according to the above formalism as a function of plate thickness as well as experimental measurements of these same quantities. The two sets of data are seen to agree quite well. Both sets show an initial rapid decrease in the amplitude of the probe output with increasing plate thickness. The phase of the probe output decreases to a minimum before increasing slightly. In the plots on the left the amplitude appears to rapidly approach a minimum value and then remain constant. The plots on the right show a more detailed view of the behavior of the amplitude near a plate thickness of 0.1". In these plots it is clear that the amplitude of the probe output increases with increasing plate thickness between ~0.1" and 0.15". The minimum in the amplitude occurs for at a thickness of approximately 2 standard depths of penetration [7]. All of the data displayed in fig. 4 was acquired using/modeling a 1/4" ID flux focusing probe operating at 10 kHz.

PHASE-AMPLITUDE DIAGRAM

The observed low frequency effects, both experimental and simulation, can be explained in terms of the phase delay of the magnetic field with depth of penetration into a conducting media. The pickup coil of the probe will link with field lines diffusing to different depths into the sample, as seen in the finite element modeling results of fig. 3. As the diffusion depth of the magnetic field into a conductor increases there will be an exponential decay in the amplitude and a linear delay in the phase of the field, as per the skin depth equation [7]. The pickup coil, linking fields from different diffusion depths in the material, will

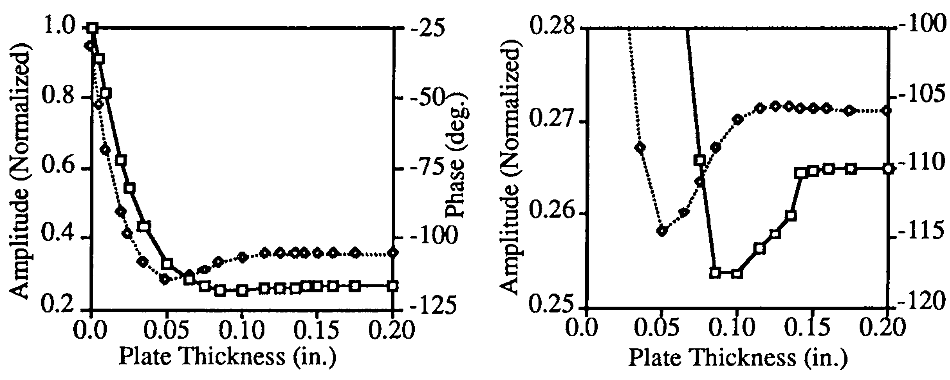


Fig. 4a. FEM results for amplitude and phase of probe output vs. plate thickness.

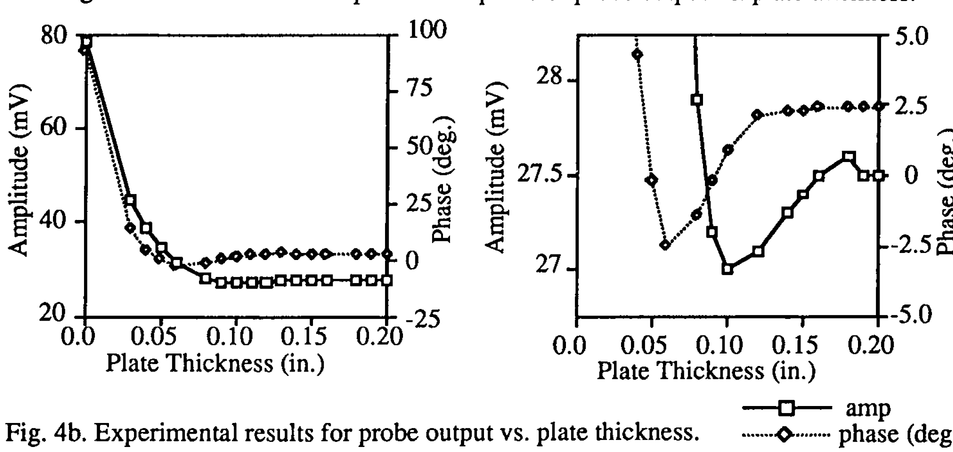
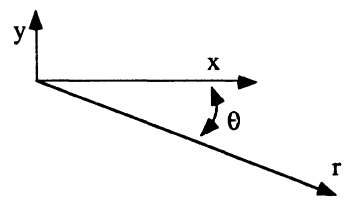


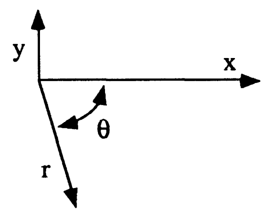
Fig. 4b. Experimental results for probe output vs. plate thickness.

then have an output determined by the vector sum of all phasors linking with the coil windings.

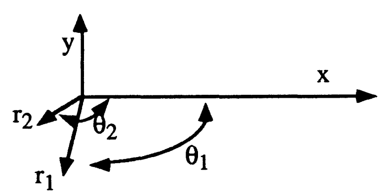
The voltage of the probe in air is governed by the diffusion of the magnetic flux into the flux focusing lens and the outer shield. The effects of the lens and shield will be assumed to remain constant as the thickness of the material under test changes. The voltage of the probe in air can then be represented by the following phasor diagram.



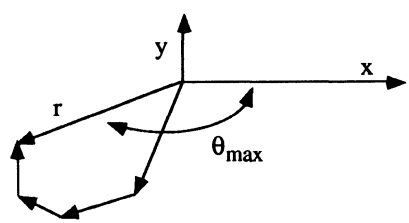
When the probe is placed on a thin conducting sample, all of the field lines which link with the pickup travel completely through the sample, causing a uniform phase delay and amplitude attenuation.



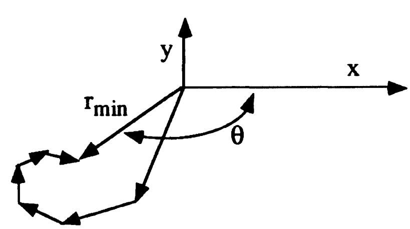
As the sample thickness increases, fields from different depths within the sample begin to link with the pickup coil.



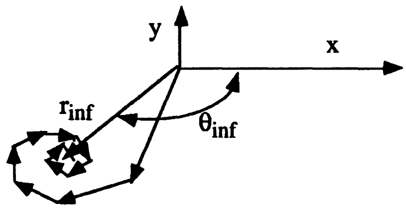
The vector sum of the individual phasors will first reach a maximum phase delay,



and then a minimum amplitude,



and spiral in toward the infinite thickness value causing a damped oscillation of both the amplitude and the phase of the output voltage.



The oscillation of the amplitude and phase of the probe output with plate thickness shown in fig. 4 follows directly from the above model. The phase shifting of the magnetic field with diffusion depth and the linking of magnetic flux lines from different depths within the material work to produce the increase in probe output with increasing material thickness of the Flux Focusing Eddy Current Probe. It should be noted that this effect is only seen when inspecting relatively thick materials, and is of an order of magnitude lower than the initial decrease in amplitude with increasing material thickness.

The oscillation of the magnitude and phase of the probe output voltage with plate thickness is not unique to the Flux Focusing Eddy Current Probe. Conventional eddy current measurements are governed by a phasor addition model similar to that given here. The traditional impedance plane display, however, is not adapted to give absolute amplitude and phase measurements so that the apparent anomaly of increasing amplitude with plate thickness is hidden, although present, in conventional eddy current measurements.

APPLICATION TO MATERIAL INSPECTION

The operation of the single and multi-layer thickness gauges designed around the flux focusing eddy current probe [3,5] will not be hindered as long as care is taken in their application. In the swept frequency measurements of the single layer thickness gauge caution must be used whenever the thicknesses exceed two skin depths of the highest source frequency. In multi-layer measurements the above two skin depth criteria should be maintained for the total thickness of the layered structure. It should be noted that these criteria are based upon work performed at a single source frequency, 10 kHz. The actual behavior at other frequencies may vary. In particular, the magnitude of the oscillations is expected to decrease with increasing frequency.

Improvements in the accuracy and dynamic range of the Flux Focusing Probe thickness gauges may be possible based on this work. Although amplitude only measurements are preferred due to their simple instrumentation requirements, an algorithm incorporating the phase of the pickup coil output may be necessary in order to extend the single and multilayer thickness gauges beyond the two skin depth limit.

SUMMARY

The apparently anomalous behavior of the Flux Focusing Eddy Current Probe in which the probe output increases with increasing material thickness has been presented. Finite element modeling was used to simulate the field interaction, confirm the behavior stated above, and visualize the field flow within the material. A model based upon the vector addition of phasors from different depths within the material under test has been presented to explain the damped oscillation of the probe output amplitude and phase with plate thickness. The phasor addition model was shown to account for the apparent anomaly and may lead to future improvements in thickness gauging with the Flux Focusing Eddy Current Probe.

ACKNOWLEDGEMENTS

The authors wish to thank Min Namkung of NASA Langley Research Center for his oversight in the Self Nulling Probe project.

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